An Improved Method of Estimating Concentrations and Related Phenomena from a Point Source Emission

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ABSTRACT

The meteorological features of a refined air pollution evaluation technique are described. Time and space variations of wind speed, dispersion parameters and capping inversions are permitted, and it is believed that the estimates of dispersion at large distances from the source are more realistic than those obtained with simple models.

1. Introduction

During the summer of 1964 Brookhaven National Laboratory was requested by the U. S. Atomic Energy Commission to review WASH 740, its earlier study of the hazards associated with major power reactors (U. S. Atomic Energy Commission, 1957). Much of the meteorological effort represented an attempt to determine the most suitable values of parameters for the accidental release considered. Discussion and literature review led, for example, to definitions of deposition and washout factors that are improvements over those used in the original evaluation, but they are unique to the specific problem and discussion of them apart from the contributions from other disciplines is not warranted.

There are several meteorological features, however, that are believed to be of general interest in hazard evaluations, and these are included in this paper. Some represent improvements in our understanding of dispersion processes, whereas others are merely improved methods for managing portions of the problem. The final result is a calculation technique that has been incorporated into a computer program. This system is noteworthy because it permits variation in source, dispersion and receptor factors generally treated heretofore as constants, and it is believed to give more realistic results at great distances than most previous studies. Complex variations in fission product release, radioactive decay and changes in meteorological conditions are all accounted for in this treatment.

2. Dispersion model

Many studies conducted over the past 15 years have left little doubt that dispersion over short distances can be described adequately by a simple Gaussian plume model (Cramer, 1959; Gifford, 1960; Pasquill, 1962). For engineering approximations especially, Eq. (1) represents an adaptable, simple expression for ground-level concentrations:

$$\chi(x, y, \sigma) = \frac{Q}{\pi\sigma_y\sigma_z\bar{u}} \exp-\{(h^2/2\sigma_z^2)+(y^2/2\sigma_y^2)\}, \quad (1)$$

where χ = concentration (units m^{-3}) or dosage (units-sec m^{-3}), Q = release rate (units sec^{-1}) or a total release (units), σ_y, σ_z = crosswind and vertical plume standard deviations (m), u = mean wind speed (m sec^{-1}), h = initial source height (m), and x, y, z = downwind, crosswind and vertical distances (m).

In many hazards analyses, one is interested in the total dose received by an individual over the entire period during which the cloud of debris is passing; in others, the concentration pattern itself may be of interest. Eq. (1) is therefore appealing, since it represents an integrated dose if Q is expressed as a total release, or concentration if Q is given as a release rate. This should not be construed as meaning that this equation with a single pair of expressions for σ_y and σ_z will apply to all situations. On the contrary, the choice of functions relating σ_y and σ_z with distance and meteorological conditions is most important to proper use of the formula, and an intelligent selection cannot be made without prior definition of source characteristics and the time scale involved.

Many such functions have been published, and it is possible to utilize any desired relationship in conjunction with this system since the development of σ_y and σ_z is relegated to a subroutine in the computer program. The authors, however, have used a power law relation of the form

$$\sigma = ax^p, \quad (2)$$

to derive the horizontal and vertical plume standard deviations actually used in this study. σ_y vs. x curves providing a good fit with field data representing the four Brookhaven gustiness classes have recently been established by Singer and Smith (1966). These plots were shown to be comparable to those derived by many

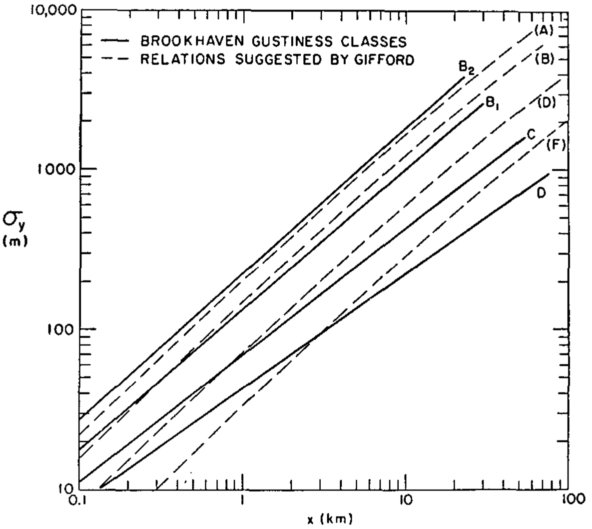

FIG. 1. Crosswind plume standard deviations. The solid lines represent Brookhaven estimates of σ_y vs. x relationships, while the dashed curves are taken from Gifford's article (1960). The B_2 and (A) curves represent the most unstable cases, and the D and (F) the most stable.

other investigators, and it is apparent in Fig. 1 that the relations used in this paper are substantially similar to those recommended by Gifford and Pasquill. It is true that plots of the Brookhaven and Gifford relations differ somewhat, especially in the slope of most stable cases (Brookhaven D, Gifford F), but there are no differences greater than a factor of 2 between 1 and 100 km. Larger differences would be quite reasonable, since Gifford's curves refer to short time periods and Brookhaven's to hourly values.

Based on indirect data and bivane measurements, a similar power law is used to relate σ_z to x. This represents a departure from the functions used by Gifford and others, but the significance of this difference will be more readily understood when other portions of the system have been described.

The specific equations used to relate σ_y and σ_z to distance and meteorological conditions are given in Table 1.

While Eq. (1) used with the above expressions describes dispersion over short distances, serious problems are encountered beyond 10 or 20 km. Meteorological conditions change with variations in terrain or in response to synoptic or diurnal factors, vertical dispersion usually reaches some upper limit, and wind patterns change. Such factors were recognized as pertinent to the original WASH 740, but limitations in knowledge, computer capabilities and time prevented their introduction.

TABLE 1. Plume standard deviations as a function of distance and meteorological conditions.

Gustiness class	σ_y	σ_z	σ_z/σ_y
B₂	$0.40x^{0.91}$	$0.41x^{0.91}$	1.03
B₁	$0.36x^{0.86}$	$0.33x^{0.86}$	0.91
C	$0.32x^{0.78}$	$0.22x^{0.78}$	0.70
D	$0.31x^{0.71}$	$<0.06x^{0.71}$	<0.20

One most interesting atmospheric feature recognized in the current study is the lack of deep radiation inversions in cities. Work by McCormick (personal communication) and Crow (1964) shows clearly that the typical nocturnal case in the city is characterized by a neutral lapse rate close to the ground with a capping inversion aloft, and it is doubtful that the deep radiation inversion characteristic of open country often exists.

3. Variation of wind with height

In Eq. (1), the parameter $\bar{u}$ is normally interpreted as a mean wind speed applying to the entire volume in which the dispersion is occurring. In short range studies, it is customary to select this wind speed accord- to the relevant meteorological conditions and the initial height of the source, but the value is then held constant throughout the computation. It is common knowledge, however, that the wind tends to increase with the height in the lower levels of the atmosphere, and it follows that the upper part of any cloud which is growing vertically will move more rapidly than that below. In the case of either an instantaneously-generated cloud or a continuous plume, this change in wind speed constitutes a dispersion mechanism different than that ascribed to atmospheric turbulence itself. The effect is, in fact, more important in terms of an instantaneous cloud where elongation is accomplished by this process, but it would also tend to reduce concentrations from a continuous emission since the mean transport speed of the plume would increase with distance if other conditions remained constant.

Management of the variation of $\bar{u}$ in the system is relatively straightforward. The optimum height for estimating the wind speed in the dispersion equation is determined by the use of a "mean equivalent wind." It is first assumed that a power law relation describes the increase of wind with height, i.e.,

$$\bar{u}(z)=\gamma z^q, \tag{3}$$

where $\bar{u}(z)$ is the mean wind at height z and q is a power normally ranging between 0.15 and 0.50, depending upon stability.

We have assumed that the concentration distribution is Gaussian, and thus the normalized vertical distribution above $z=0$ is

$$\chi(z)=\frac{2\alpha K}{\sqrt{\pi}}\exp(-\alpha^2z^2), \tag{4}$$

where

$\alpha^{-1}=\sqrt{2}\sigma_z$,

K = proportionality constant, and

$$\int_0^\infty \chi(z)dz=\frac{2\alpha K}{\sqrt{\pi}}\int_0^\infty \exp(-\alpha^2z^2)dz=1.$$

We can then establish a quantity W that represents the "mean equivalent wind," depending upon the vertical concentration distribution and the wind profile, i.e.,

$$W=\int_0^\infty \chi(z)\bar{u}(z)dz, \qquad (5)$$

where $\chi(z)$ now serves as a weighting function. A uniform wind of magnitude W will produce the same result as $\bar{u}(z)$ within the integral.

By substituting (3) and (4) into Eq. (5), we obtain the optimum height $\hat{z}$ where $\bar{u}(z)=W$, i.e.,

$$\frac{2\alpha K}{\sqrt{\pi}}\int_0^\infty \exp(-\alpha^2 z^2)\gamma z^q dz=W=\gamma\hat{z}^q, \qquad (6)$$

which reduces to

$$\hat{z}\alpha=[\Gamma\{q(+1)/2\}/\sqrt{\pi}]^{1/q}\approx 0.44,$$

where $\hat{z}\alpha$ ranges between 0.40 and 0.48 depending upon stability. Therefore

$$\hat{z}\approx 0.62\sigma_z, \qquad (7)$$

and thus the relationship between the "mean equivalent wind" and the vertical standard deviation of the cloud is

$$W\approx\gamma(0.62\sigma_z)^q. \qquad (8)$$

It should be noted that if the source is at an elevation h, the mean equivalent wind is assumed to be that appropriate for h until $\hat{z}\geq h$.

It is interesting to note the difference between the assumption of a constant wind and the use of Eq. (8). The solid line in Fig. 2 represents the mean equivalent wind used in this evaluation to represent dispersion from a source originating 5 m above ground under typical daytime conditions. The wind increases rapidly with distance until vertical cloud growth stops at 14 km owing to a 1500-m inversion led aloft. If one assumed a constant wind appropriate for a 5-m source height, indicated by the lower dashed line, the mean equivalent and constant assumptions would differ by a factor of 3 by the time the plume reached 5 km.

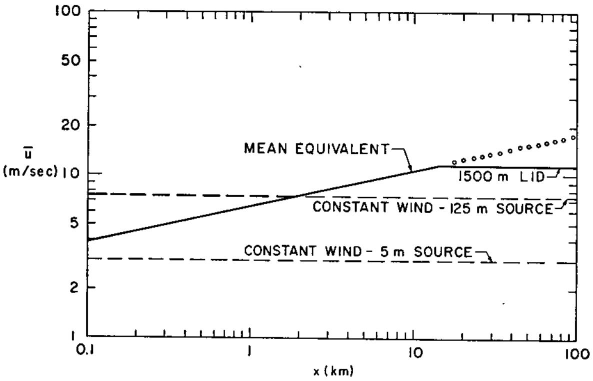

FIG. 2. Comparison of mean equivalent and constant winds for typical daytime conditions. The solid line represents the wind speed as adjusted for the growth of a cloud originating at ground level in the Brookhaven system. In the case shown, this adjusted wind speed became significantly different from a constant wind appropriate for a ground-level source after a short distance.

The wind appropriate for a source at 125 m, on the other hand, would initially be represented by the upper dashed line in this model (since the cloud first disperses both upward and downward) and would then follow the solid line after the intersection at 2 km. Here, the difference between the Brookhaven system and a constant wind value chosen for a 125-km source would never reach a factor of 2 with a lid of 1500 m.

In terms of concentration, the use of the mean equivalent wind tends toward reduced values, particularly if a ground-level source is involved.

One factor not included in this evaluation is the variation of wind direction with height. Like the change in wind speed, this is a well-known feature of the lower atmosphere, but it is not completely clear how it affects dispersion. Pronounced directional shear should tend to increase the crosswind dimension of the plume and it is probable that the effect is partially accounted for in the σ_y values.

This neglect of directional shear at first seems conservative, since the tendency would be to decrease the concentration directly downwind. The *effect*, however, may not actually be conservative at all, since widening the plume in an area containing many receptors could affect a larger number with lower, but significant, concentrations.

4. Limitation of vertical dispersion

Despite the fact that one cannot cite complete corroborative data, it is certain that airborne pollutants released from a low level do not continue to disperse indefinitely in the vertical. Observation of the top of the haze layer from an aircraft is sufficient qualitative proof that an upper boundary to dispersion usually exists below the tropopause, and Holzworth (1964) has used synoptic meteorological data to prepare estimates of this upper limit of the mixing layer throughout the United States. It is somewhat surprising to find that his investigation suggests relatively modest heights for the capping lid, even during the daylight hours. Typical values for the depth of the daytime mixing layer would be 1500 m in summer and 500 m in winter. In both summer and winter, a value of 200 m would represent the usual nocturnal case.

Existence of this limit has probably had little influence on the relatively short range dispersion studies reported in the literature, primarily because the observations have not extended downwind far enough for the effect to be observed. It is a feature, however, to be considered in long range evaluations.

A problem arises in deciding at what point the lid effectively stops cloud growth. Meade (1959) has suggested that vertical growth might be stopped when $\sigma_z=H/2.15$, but this assumes a cessation of mixing while a considerable vertical concentration gradient remains below the inversion. Pasquill (1962) also discussed the question, and decided that σ_z should become a constant when it is equal to the depth of the mixing layer. He based his selection on the assumption that the vertical distribution of material within the layer should be nearly uniform with height at this point. The authors agree with Pasquill's reasoning, and equating $1.25\sigma_z$ with the inversion lid would give a ground-level concentration consistent with a completely uniform distribution with height according to the mathematical model used. This identity is therefore adopted in preference to $\sigma_z = H$, although the difference between the two is of little practical significance.

Now that the wind profile and inversion lid treatments have been introduced, it becomes appropriate to compare the Brookhaven treatment of σ_z with Gifford's. Fig. 3 shows the σ_z vs. x curves suggested by Gifford, the power law relations used by Brookhaven and three horizontal lines depicting the typical upper limits of σ_z in the United States, based on Holzworth's data.

On the left-hand side of the graph one sees a sharp discrepancy between Gifford's suggested curves for unstable cases (A) and (B) and the Brookhaven B_2 and B_1 plots. Gifford's curves agree better with the idea that vertical turbulence increases with height in the lower layers of the atmosphere under such conditions, but the authors (1966) have examined this question in their recent study of dispersion and fail to find sufficient direct observations of σ_z to substantiate the apparent upward curvature. In fact, it is possible that the curvature of the derived σ_z plots reported by most investigators could result from neglect of the increase of wind with height. The key point is that the data required for a definitive choice are lacking.

Whichever unstable plot may appeal to the reader, the presence of the horizontal lines representing cessation of vertical expansion of the cloud serve as reminders that no conventional approach is reliable when the depth of the mixing layer is limited.

The inverse discrepancy is observed in the neutral and stable cases, where the Gifford plots curve to the right and the Brookhaven representations are straight lines. Here, also, the presence of an inversion lid would make the discrepancy less significant than it would first appear, since all vertical growth would stop at a low altitude. This, of course, is implied in Gifford's curve F and in his description of the problem. The authors also have qualitative data showing that the rate of change of σ_z with distance is strongly dependent on height during stable conditions, and for sources 50–100 m above ground, σ_z may remain nearly constant. Thus, the Brookhaven curve D in Fig. 3 is applicable only to a low-level release.

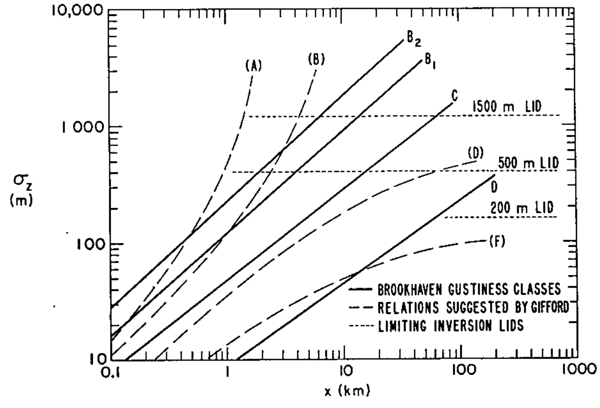

FIG. 3. Vertical plume standard deviations. The plots shown are counterparts of those in Fig. 1, in this case representing vertical cloud growth. The horizontal dashed lines show where vertical growth would cease with the indicated inversion lids.

Including the wind profile and inversion lid concepts in the computations is not at all controversial in principle, but it is clear that better understanding of both phenomena would refine estimates such as these.

5. Change in conditions with time and distance

Even less controversial is the idea that meteorological conditions may change with time and distance. In fact, one of the major criticisms of the original WASH 740 was that conditions were allowed to remain unchanged for unbelievable distances. It is possible to take such changes into account.

The first step in the procedure is to establish time and distance scales as references. The latter is necessarily present as a basic part of the computations, but a time scale requires a separate computation. Inasmuch as the mean equivalent wind may vary from one distance interval to the next owing to the change in wind with height, the program computes the time appropriate to each distance interval and also records the accumulated time.

At some designated point in time, a change in dispersion conditions is accomplished by assuming that the Gaussian plume distribution suddenly begins to change at a different rate, retaining the same mathematical form but following a different power law function. The details are easily understood when related to Fig. 4. Assume that dispersion has proceeded under neutral conditions (σ_y increasing according to curve C) out to a distance x_1, at which point conditions suddenly change to those typical of the daytime. This implies that the crosswind distribution of the cloud represented by σ_y begins to increase according to the B_1 curve, although at the moment of change the value of σ_y is that specified by the C curve. The transfer is accomplished by defining a quantity Δx as the numerical value of distance between the points having the same σ_y values when the change occurs. Dispersion from this point on is computed according to the B_1 curve on a distance scale of $x+\Delta x$, but it is reflected in the output according to the original scale x. In the figure σ_y is represented by the heavy line for the entire course of the dispersion. It increases rapidly immediately after the change-over and asymptotically approaches the typical daytime curve at great distances. Δx in the example shown is -0.35 km, so that the σ_y value for 1 km is represented by the B_1 curve at 0.65 km, etc.

An identical method is used to change σ_z, and it is

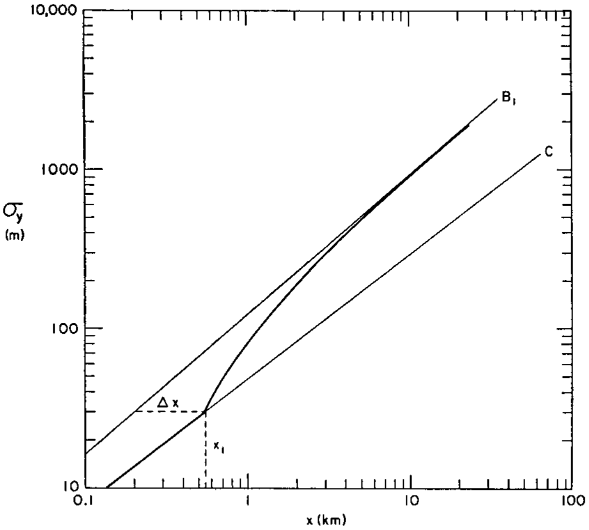

Fig. 4. Crosswind standard deviation under changing conditions. The heavy line shows the relation between σ_y and x that would apply if a change from neutral to typical unstable conditions occurred at a distance x_1.

also possible to adjust for a sequence of changes in either σ_y or σ_z simply by substituting new values of Δx each time a change occurs.

Adjusting for a change in dispersion conditions involves a few additional complications. In the model as described so far, provisions have been introduced to take account of a lid capping the dispersion at a particular height and a wind speed which is allowed to change with height but does not change in terms of the overall profile. It is clear that either or both of these factors may alter with the dispersion conditions.

The variation in the height of the lid presents no serious problem. If the height increases, as it naturally would in a change from stable to relatively unstable meteorological conditions, one simply introduces a new value of H at the time the dispersion conditions are changed. If the vertical standard deviation has already become constant prior to reaching this point under the initial dispersion conditions, it will again increase until it reaches the height appropriate for the new condition. If it has not reached the original lid, it will continue to increase until the new one is encountered.

The reverse situation requires an additional assumption. Suppose that dispersion proceeds under relatively good conditions and that a stable structure either is encountered or forms with a dispersion lid at a lower altitude than has already been reached by the cloud. The new lid would be an effective barrier for either upward or downward dispersion, and the assumption is made that σ_z can never decrease. Therefore σ_z is held constant when a change from unstable to stable conditions occurs involving a decrease in H.

The change in overall wind speed (a shift in the magnitude of the entire profile) is allowed to occur abruptly. When the plume undergoes a change from type one of dispersion condition to another, an appropriate wind for the new condition and the existing height of the cloud is introduced. This may actually produce a discontinuity in the concentration curve at that point, but it is of little practical significance since there is no reason why this adjustment cannot be introduced gradually by a series of steps in the program.

One of the more important factors is the possibility of a change in mean wind direction occurring at some point during the period of emission. Such a change would spread the material over a far wider horizontal area than is possible by any simple turbulent fluctuation.

The computer program developed for this study does not account for this possibility, however, for two reasons. In the first place, the mean wind direction may persist unchanged for a large number of hours. This does become less probable with time, but a mean direction substantially constant for a period of 24 hr has a relatively high probability of occurrence.

The second reason for ignoring the possibility of a wind direction change is that in most postulated accidents both the leakage mechanism and the radioactive decay tend to cause the bulk of the release to occur within the first 4–6 hr. Constant wind directions for periods of this order are very common, and it was therefore considered inappropriate to be unduly concerned with direction changes. Further, it is always possible to separate computations of this type into periods having different mean directions, and to estimate the total effect by an additive technique. This too, is a simple computational procedure.

6. Washout and deposition

The reactor hazard evaluation is almost always confined to particles of relatively small size, generally about 1 μ and not exceeding 10–20 μ. The most appropriate mathematical evaluation for this problem is still considered to be that proposed by Chamberlain (1955), although the question is under investigation both here and abroad. The computer program can develop both concentrations corrected for these removal processes and estimates of the ground deposition itself on the basis of the following formulas, which represent Chamberlain's approach converted to the simple Gaussian form:

Deposition

$$D=\text{Eq. (1)}\cdot V_g\cdot\exp(-B), \tag{9}$$

where

$$B=K\,[-\exp(0.5h^2/\sigma_z^2)+\Gamma_\infty\{(2-a)/2\}-\Gamma_\xi\{(2-a)/2\}],$$

$$K=\{(a+1)/a\}\,V_g(\sqrt{2}/\pi)\,t/\sigma_z,$$

$$a=(1-q)/q,$$

$$\xi=0.5h^2/\sigma_z^2,\quad\text{and}$$

$$D=\text{deposition (units m}^{-2}).$$

Washout

$$P(x,y)=\{\Lambda/(\sqrt{2\pi}\bar{u}\sigma_y)\}\exp(\Lambda t)\exp-(y^2/2\sigma_y^2), \quad (10)$$

where the new symbols introduced are

V_g = velocity of deposition (m sec^{-1}),
Λ = proportion of cloud removed by rain (sec^{-1}) and
P = washout (units m^{-2}).

Neither equation requires special discussion, nor does either influence the adjustments to dispersion already described.

7. Source and receptor factors

Among the deficiencies of the original WASH 740 and many similar studies were over-simplifications regarding sources and receptors required to make the problem tractable. For example, although most accidental releases occur as some decreasing function of time, earlier studies usually assumed that the release occurred continuously at a steady rate, or that the entire batch of material was emitted instantaneously. Since flexibility in representation of such problems is considered most important in this program, a varying release from the source is handled by a series of discrete calculations which can be repeated as often as necessary. The concentrations (or related data) resulting from the initial portion of the emission are computed for the entire distance range of interest, followed by similar complete calculations for additional portions of the release. In the final output both the individual contributions and the cumulative totals are available if desired.

Normally the value of the emission for each time period includes radioactive decay that has already occurred, but obviously this would not account for further decay as the material proceeds downwind. The latter is accomplished by an exponential correction term which can be changed as needed, and which makes use of the time scale developed for adjusting to changes in meteorological conditions. For each portion of the emission, therefore, Q is automatically corrected so that the concentration at any given distance reflects the decay after release.

This same function can be used, of course, to simulate processes other than radioactive decay that might deplete the cloud during its transport. Chemical changes, for example, might make a significant difference in the effect of the material and they can usually be represented by this type of adjustment.

The final problems dealt with are those of a purely practical nature. One is usually interested in some representation of the effect of an emission as well as a plot of concentrations or depositions downwind. The system, therefore, incorporates a procedure by which a function relating the receptor density to the distance from the source is used in conjunction with the data already developed to express the results in terms of the number of receptors affected by given levels of dosage or concentration. Similarly, where deposition is the end product, the program defines areas affected by various deposition levels.

8. Examples of the computations

The authors have searched in vain for broad generalizations distinguishing the results produced by this computation method from those of less sophisticated models. The interplay of factors is so complex that one cannot really find a consistent set of differences. It would be possible to compare results obtained with this program to others, but a thorough study would entail an enormous number of graphs and even then the particular interest of a given reader would inevitably involve still another unique problem. Therefore, only a few examples stressing some of the major points are presented.

Figs. 5 and 6 are plots of the centerline concentrations found under typical daytime and nocturnal conditions, respectively (B_1 and D cases, Table 1), if no deposition, washout, radioactive decay or other depleting factors are operative. In Fig. 5 the heavy straight line at the upper left-hand portion of the graph represents the centerline concentration from a ground level source released at an arbitrary rate of 10^{10} unit sec^{-1}. The slope of this portion of the curve is somewhat steeper than that normally predicted for typical daytime dispersion owing to the fact that the

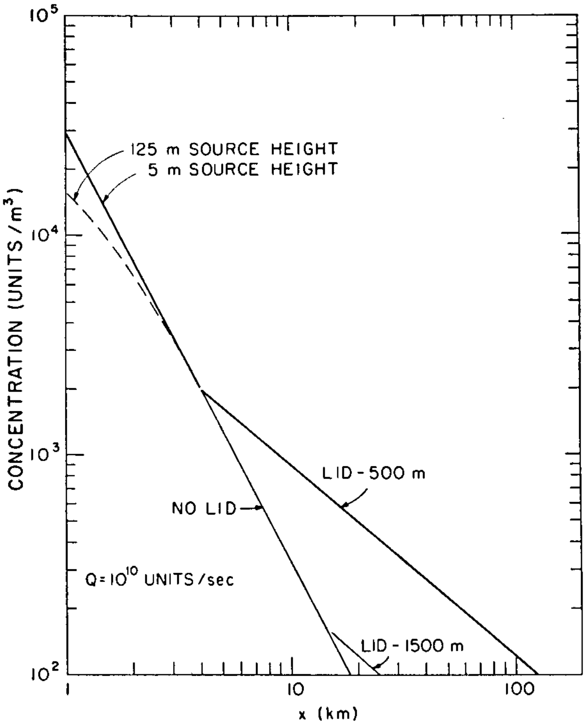

FIG. 5. Centerline concentrations, typical daytime conditions. The heavy line represents the decrease in concentration with distance that would be found with a typical unstable lapse rate capped by an inversion lid at 500 m. The influence of higher source elevations and a different lid is also shown.

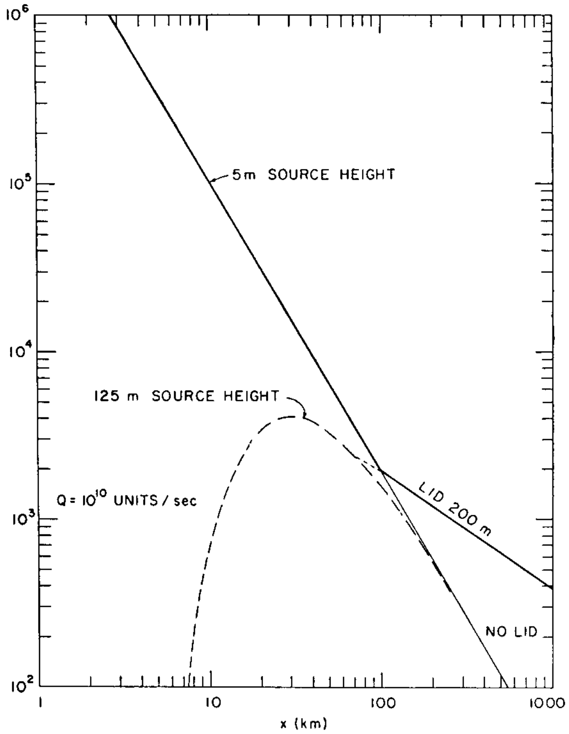

FIG. 6. Centerline concentrations, typical nighttime conditions. A counterpart of Fig. 5, computed for stable conditions.

wind is increasing with height and reducing the concentration. At 4 km an abrupt change in slope occurs where an inversion lid limits further increase in both vertical dispersion and the wind speed. The slope of the concentration curve from this point on is far less steep than it would be if no upper limit to the growth of the cloud were present, and a lid at 500 m would increase the concentration at 20 km by a factor of 5 over unconfined vertical dispersion. It is also clear that an initial source height of 125 m instead of 5 would have practically no influence on the concentration pattern beyond 2 or 3 km.

The same sort of plot for a nocturnal, stable condition is shown in Fig. 6. At the closest distance shown one finds the usual difference between stable and unstable conditions with a concentration more than 2 orders of magnitude higher than that observed in the daytime. Here also the concentration initially decreases somewhat more rapidly than it would in conventional models owing to a gradual increase of wind as the cloud grows vertically. In this instance the kink in the plot representing the effect of the 200-m lid is encountered at 100 km, after which further decrease in concentration is accomplished entirely by lateral dispersion. As before, the dashed curve represents the concentration directly downwind of a source at 125 m. Here a maximum ground level concentration is reached at 30 km, approaching thereafter the pattern typical of the ground level source. In the earlier discussion, it was noted that σ_z of an elevated plume probably increases at an exceedingly slow rate under stable conditions, and this portion of the example is unrealistic. It is actually unlikely that the elevated plume would disperse to ground level in a distance less than 200 km. For simplicity, however, the D curve of Fig. 3 has been used to represent both ground level and elevated sources.

Fig. 7 has been prepared to show the effect of changing meteorological conditions during the course of dispersion. The solid curve initially represents the concentration that one would expect under very stable conditions in open country, and after 0.2 hr of travel (2 km) the plume comes under the influence of a neutral condition typical of the nighttime hours over a large city. An extremely rapid decrease in concentration occurs within the first kilometer after the change, with the rate of decrease tapering off thereafter. To prevent confusion no lid has been assumed for this case, and the city condition has been allowed to continue to the end of the graph. The dashed curve represents a change from typical daytime dispersion

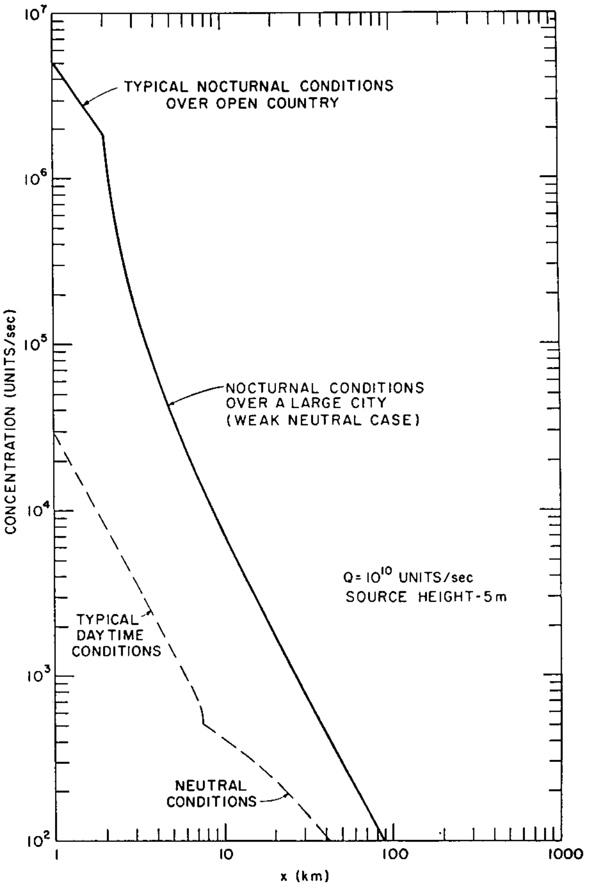

FIG. 7. Centerline concentrations under changing meteorological conditions. The solid line shows the concentration curve associated with a plume undergoing dispersion first under stable conditions and then under weak neutral conditions after 2 km. The dashed line shows the change with another pair of conditions.

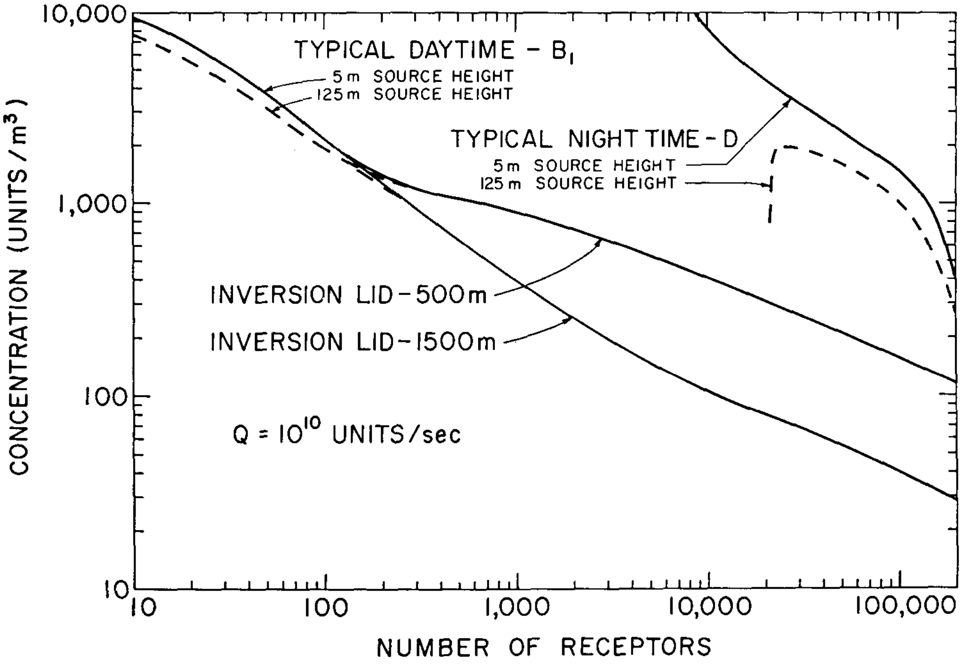

FIG. 8. Receptors affected under various meteorological conditions. The plots are the end product of the computation system relating the number of receptors to concentration levels for the cases indicated.

conditions to neutral conditions also occurring at 0.2 hr after the initial release. The distance of the change-over is approximately 6 km instead of 2 owing to the more rapid travel of the cloud. The extremely steep slope of the concentration curve immediately following the time of change-over is associated with the discontinuity introduced by allowing the entire wind speed profile to shift abruptly at this point.

It is apparent that a continuous release could often involve complicated changes, and it is for this reason that the ability to handle hourly sections of the release separately becomes valuable. For example, if one assumes a change in meteorological conditions occurring at a fixed clock time, each section of the plume will undergo a change in conditions at a different time after its release, the change occurring earlier and earlier as the release continues. If, on the other hand, the change is associated with distance (e.g., the edge of the city) instead of time, the condition would always change at a fixed distance regardless of the time of release. Either case is easily managed.

The final graph (Fig. 8) gives some idea of the complexity that is really associated with effects rather than concentrations when a flexible model is used. Fig. 8 is a plot of the number of receptors affected by concentrations of various levels during the typical daytime and nocturnal cases shown in the previous examples (Figs. 5 and 6). Also introduced into the computation is an expression relating the receptor density (R) to distance,

$$R=200x^{2.83}. \qquad (11)$$

As with the concentration curves, it is apparent that it makes little difference whether the source is elevated or at ground level during the daytime. The importance of the lid, however, is quite obvious in the right-hand portion of the daytime curves, where at levels of concentration ranging from 50–500 units m^{-3}, the difference between the number of receptors affected is a full order of magnitude.

The two curves representing stable conditions appear in the upper right-hand portion of the diagram and here it is obvious that the height of the source is more important than any other factor. If the release occurs close to the ground the number of receptors affected is very large even at high concentrations, but if the source is elevated the entire left-hand portion of the curve is eliminated.

In all cases, the unfamiliar curvature of the plots is associated with the complex interaction among factors such as the change of wind with height, effect of the lid and the distribution of receptors.

9. Research implications

An important by-product of a study such as this is that the weaknesses in both knowledge and application are placed in bold relief. While the system described is considered an improvement over that used in the original WASH 740, much remains to be done.

Most apparent to the authors is the importance of proper definition of the vertical distribution of the cloud and our lack of detailed knowledge about this problem. Measurements of σ_z are hardly a prominent feature of dispersion literature. True, most investigations result in *estimates* of σ_z or a related parameter, but these are usually derived quantities rather than direct measurements.

The same can be said of the inversion lids. Recent research has helped define the upper limits of atmospheric mixing, but field studies are needed to ascertain how such lids actually affect concentration patterns.

Study of vertical wind shear is perhaps more important than it would seem. The change in wind direction as well as speed may play an extremely important part in long range dispersion, and both theoretical and field work is indicated.

The possible effect of terrain has been restricted in this study to the likelihood that meteorological conditions will change with distance. One should also recognize that prominent terrain features may have important effects on dispersion and upon the net transport of the entire cloud in the horizontal and vertical. Appropriately designed field experiments are obviously in order.

Because only meteorological features of general interest are included in this paper, the study of such phenomena as the removal of particles from the atmosphere and the rise of buoyant clouds has not been stressed. For certain aspects of hazard evaluations, however, each of these problems may be of equal importance with the purely meteorological factors.

It is interesting also to see that a more effective presentation of climatological data is needed. The typical summaries often cannot be interpreted properly. For example, persistence in the sense of the number of hours or days that a given condition remains unchanged is a common part of typical hazards analysis climatology, and yet it is not directly as indicative of ground level concentration as studies of repetitive conditions might be.

Closely related to the development of more suitable climatology is the problem of more effective use of standard instruments. Research equipment can, of course, supply the data needed for hazard evaluations, but every attempt should be made to extract the maximum information from standard observations.

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